Systems thinking and practice: a review and analysis of key ideas and their implications for practice in design & technology education

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Systems Thinking and Practice; A review and analysis of key ideas and their implications for practice in Design & Technology education

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Abstract

This paper provides an historical overview of the development of systems thinking as an analytical tool in a wide range of disciplines. The types of systems diagram that have been developed to support systems thinking are summarised and grouped. Against this background the development of systems thinking within D&T education is described and the systems content of a range of current D&T texts is analysed. The paper concludes both that the penetration of systems thinking into D&T education has been weaker than in many other disciplines and that current texts are providing limited support for pupils’ development of systems thinking.

Keywords

Systems, Systems diagrams, Control, Modelling, Design, Analysis

Introduction

Humans live in a rich and complex (or messy) environment; some of it natural and some of their own making. Systems Thinking is a way of grappling with aspects of this environment, which presumes that what is observed is caused by understandable relationships between elements that can be defined. The aspect under investigation is called the system and its elements sub-systems. Often a system will itself be viewed as a sub-system of a larger system, in the same way sub-systems may be systems in their own right made up of ‘lower’ order sub-systems. The essence of a systems view is that one doesn’t need to know how a sub-system operates, it is sufficient to know what it does within the larger system. Systems and sub-
systems are linked by some form of information flow between them. Information flow into a system is generally called an ‘input’ and information flow out, an ‘output’. Very often, a systems description will be a simplification (Ashby, 1964) either out of mathematical necessity or because a very useful way of describing the world around us is to simplify it.

The Development of Systems Thinking

Skyttner (1996) has described how this ‘expansionist’ or ‘top-down’ way of viewing the world first appeared in the 1920s as a response to the failure of reductionist approaches to explain emergent biological and social behaviours. However, systems thinking did not become widespread until after the Second World War as computers became increasingly important. Computers allowed systems to be modelled and explored more easily and rapidly. Equally importantly, in themselves computers provided both an example of an understandable yet complex system and a new way of looking at how aspects of the environment might operate. For example, the view that the human brain is, in essence, a computer soon became widespread. This way of viewing the world has now entered the general consciousness so successfully that the word ‘system’ is in general use in English, usually as an up-market way of describing organisations and relationships (the Class system, the Parliamentary system, an airline booking system etc).

Two specific strands of systems thinking that emerged from the war effort were Cybernetics and Operational Research. Cybernetics sought to apply systems thinking to living organisms by analogising the living with physical systems (Weiner, 1948). A central feature of all cybernetic approaches is the recognition of feedback cycles that allow the outputs from the system to be used as inputs. However, the term ‘cybernetics’ eventually generalised to encompass much more than just living systems and, for some, became synonymous with ‘systems thinking’, particularly in engineering situations, such the development of robots, but

Operations (or Operational) Research (OR) developed as a pragmatic approach to handling military strategic decision making where there was not time or intelligence to marshal all the facts before a decision was made. Key elements of OR (Skyttner, 1996) are that:

- It is more important to know what happens than to understand why it does;
- It is better to concentrate on the main features of a problem and ignore small details;
- One should concentrate on today’s problem and be aware that both prerequisites and solutions may quickly become obsolete.


In the 1950s, there was a move to unify the various strands and applications of systems thinking that had emerged into a General Systems Theory (GST). Bertalanffy (1955) began to publish ideas on a systems theory, first developed in the 1930s, which had characteristics independent of the field to which the theory was applied. At the same time, Boulding (1956) published a highly influential system hierarchy that suggested a universal application of systems ideas. Thus GST (and later Systems Science) started to develop into a discipline of its own with the purpose that it should define a ‘law of laws’ applicable to a wide range of other disciplines. This lead to a burst of activity in the field over the next couple of decades with systems thinking influencing most branches of knowledge (Beishon & Peters, 1972; Faurre & Depeyrot, 1977; Singh, 1987; Wilson B, 1991; Skyttner, 1996). That a search for journals with ‘System’ in the title turns up 218 ‘hits’ is indicative of the breadth of penetration of systems ideas.
Inevitably engineering disciplines (including computing) have made significant use of systems ideas developed from cybernetics (e.g. Hall, 1962; Mesarovic, 1964; Jenkins GM, 1969; Boot, 1973). These ideas have supported both the analysis of problem situations and the design of new solutions.

The conceptual link between the workings of computers and that of the brain has ensured that psychology has not escaped the application of systems ideas (e.g. Newell & Simon, 1972; Pask, 1975; Sayre, 1976; Kohonen, 1977). Bruner (1960), while not talking specifically in terms of systems ideas, laid great stress on the need to structure the approach to teaching any particular subject matter, in a way that is very suggestive of systems thinking.

Equally, in a development of OR, the use of systems ideas to inform thinking about a broad range of human systems and their management was particularly successful (e.g. Forrester, 1961, 1968, 1969, 1971; Friend & Jessop, 1969; Lande, 1970; Checkland, 1971, 1981; Maurer, 1971; Beer, 1967, 1972; Optner, 1973; Warnier, 1979). Education itself has not been ignored (e.g. Smith & Smith, 1966; Levine, 1971; Thomas, 1971; Gillham, 1981). The approach to applying systems ideas in these areas has however developed significantly. In the early days, it was assumed that engineering approaches could be equally well applied to social situations. However, this ‘hard’ approach, with its supposedly neutral emphasis on defining and imposing solutions using quantitative methods, became widely criticised for, among other things, its deterministic view of human nature, its tendency to support authoritarian approaches to management and its weakness in dealing with internal conflict in systems (Checkland, 1978). Consequently, a ‘soft’ systems approach was developed whose goal was the understanding of complex social systems using qualitative descriptive models. These models were not always of the ‘real’ world but rather of social or mental relationships or of (often conflicting) views of reality and had as their aim informing better management rather
than providing optimised solutions (Checkland, 1999). ‘Soft’ systems approaches have been,
in turn, subject to analysis from a critical theory perspective (inspired, for example, by
Habermas, 1973) for their supposedly ‘value-free’ approach, their assumption that all
participants will be equally able to voice their views in unconstrained ways and their
insistence on agreement on ends by all participants. Perhaps the most damning criticism of
‘soft approaches is that their application to the real world tends to lead to conservative
recommendations for change despite the analysts’ usually radical intentions (Jackson, 1987).
From this have developed ‘critical’ systems approaches in which explicit social theories are
brought to bear on the analysis of social situations. The social theories are used to analyse and
authenticate the systems analysis, leading to deeper understanding in the social participants
that enables them to rationally select appropriate social strategies (Flood & Jackson, 1991).

A Typology of Systems Diagrams

A consequence of the developments outlined above is that systems thinking has developed in
a range of different ways for different purposes. More particularly, analysts at work in
different disciplines have developed diagrams to express their particular understanding and
application of systems ideas. There appear to be at least nine different diagram types in
general use under the title ‘system’ diagram, plus many variants which are not recorded here.
Common to all these diagrams is the use of blocks of some kind (and a wide range of shapes)
connected by lines; what differs is the meaning given to the blocks and lines.

Type 1

Here blocks represent functions (that may be mathematically defined) and lines represent
signals or messages passing between the blocks. These are often called ‘block’ or ‘structural’
diagrams and are typically found in engineering contexts and other ‘hard’ systems
approaches. Diagram 1 shows a classic example given by Bertalanffy (1972: 34):
A more common version, often used in secondary education, is shown in Diagram 2:

A broader range of block symbols may also be used, for example to distinguish elements with different functions (Haslam et al, 1993). Ladder Logic, used extensively in industry as a programming tool, is also a Type 1 diagram.

**Type 2**

In this case an analogy with fluid flow is used; lines represent ‘pipes’ through which information flows and blocks represent valves that control the flow and tanks that show levels. A mathematical definition generally underlies the diagrams, which are called ‘systems dynamics’ diagrams and are commonly used to illustrate the dynamics of human behaviours (e.g. Forrester, 1961, 1969, 1971; Meadows et al, 1972, 1992; Coyle, 1978). A typical example of such a diagram, used by Meadows et al (1992: 24), is shown in Diagram 3:
Other commentators use a wider range of defined symbols, such as that in Diagram 4 (Forrester, 1968: 7-1):

Diagram 4

One reason for the popularity of such diagrams is their use in computer based modelling systems (Mellar et al, 1994).

Type 3

Flow charts or diagrams are used to describe a series of events, shown by blocks, and the order in which the events take place, shown by the connecting lines. These are typically used in the development of computer based systems because of the way in which they map closely to computer languages (Boot, 1973), but are also used more generally, especially when
systems theorists wish to describe decision making processes (e.g. Friend & Jessop, 1969).

Diagram 5 shows a simple example from a computing context.

**Diagram 5**

**Type 4**

Network (or ‘bond’) graphs have developed from Informatics (a branch of systems theory dealing with the flow of information). Here the connecting lines are links between nodes and
the resulting graph provides a map showing how nodes are related (Dixhoorn & Evans, 1974). As well as being used to describe information and communication networks these graphs can also describe relational networks (for example decision making relationships in an organisation) (Evan, 1966; Friend & Jessop, 1969). Diagram 6 shows a simple communication network (Skyttner, 1996: 233).

Type 5

In a state machine, or state transition, diagram the blocks represent all the possible states of a system and the lines define how the system moves between states by stating what triggers the movement between states and how it is achieved (Faurre & Depeyrot, 1977) as in Diagram 7 (BT, 1993: 26):
Type 6

Concept maps are a well-known tool for eliciting the mental links between concepts that an individual holds (White & Gunstone, 1992). The same idea, known as conceptual models, human activity systems (HAS) or strategy graphs, is also used in systems analysis to show the conceptual relationships between parts of a system. Here the blocks represent (usually qualified) verbs describing system activities and the relationships between them as in Diagram 8 (Wilson, 1991):
Type 7

In organisational structure diagrams, the blocks represent elements of an organisation and the lines the communication or control links between them. In essence, these are very similar to Type 4 diagrams (Burack, 1967; Friend & Jessop, 1969).

Type 8

In a variant on Type 7 diagrams, transaction structure diagrams describe the personal transactions within organisations. The diagrams have the same components and basic structure as Type 1 diagrams but the blocks indicate the activities of individuals or groups (with different blocks for those inside and outside the organisation) and lines indicate the possible paths of interaction between them (Thompson, 1962).

Type 9
Decision diagrams are yet another variant on Type 1 diagrams where the arrows represent information flow (couched as 'situations' and 'actions') in a social system and blocks represent the decision makers that change that information (act on situations). The resulting closed loop is called an 'action circuit' (diagram 9, Friend & Jessop, 1969):

![Diagram 9](image)

Three things emerge from this summary of system diagram types. Firstly, the importance of diagrams in explicating the work of systems theorists. Secondly, the critical need to define very clearly the intended meaning of diagram elements, since diagrams that look very similar may describe quite different things; the reverse can also be true. Not all the texts drawn upon
in this analysis are equally good at achieving this definition, in some instances the neglect of definition destroys much of a diagram’s worth. Thirdly, the purposes that diagrams are put to; usually either to analyse an existing systems or to support the design of a new one.

**Systems Thinking in Design & Technology**

Systems ideas crop up in a number of curriculum areas, but have particular pertinence in D&T where a main focus of work is in enabling pupils to both understand and design within complex situations. Perhaps the most significant influence on the development systems thinking within D&T teaching was the, increasingly explicit, inclusion of systems language in the UK D&T National Curricula from 1990 onwards. Each iteration of this Curriculum has of course been strongly influenced by practice in classrooms and the thinking outlined below.

It should be noted that, despite the wide-ranging activity in systems theory noted above, the (academic) literature within D&T is very sparse indeed. What follows is a comprehensive, albeit brief, summary of the development of systems thinking within the subject. However, many developments were communicated mainly through the medium of texts aimed at pupils and their teachers, where practical applications were to the fore and theorising kept to a minimum. Some of these texts are examined in the next section.

Bevis (1983) makes an early case not only for electronics in the D&T curriculum but also for a systems approach to it, defined using classic Type 1 diagrams. Following this, contributions from Martin (1987,1990, 1993), Thompson (1990), Steeg (1995) and Branson (1999) continued to discuss specifically systems based approaches to electronics teaching aided by Type 1 diagrams. Systems approaches to computer control technologies have also been addressed in a series of articles by Bostock (1994a, 1994b, 1995) which are based on the use of Type 2 diagrams. During this period the IEE journal Electronics Education also maintained
(editorially at least) consistent and practical support for systems approaches to electronics and control education. Note that all of these are examples of 'hard' systems thinking. There has been very little work at all relating systems thinking to other important aspects of D&T, such as designing or product analysis, that are at the heart of much systems thinking in the wider world. There appears to be just one paper published that provides D&T educators with an overview of systems ideas and offers a broad view of their applications (including their use in D&T management), though it introduces no practical support for their development (Anon, 1990). A comprehensive review and comparison of design processes in D&T education fails to identify any design models that have systems elements (Johnsey, 1995).

**Systems ideas in Current D&T Texts**


- The use of diagrams to support systems thinking is generally restricted to Type 1 and Type 2 diagrams (following the pattern found in the D&T academic literature), with Type 2 diagrams being largely applied to control programming. This latter emphasis is encouraged by popular control programming environments based on Type 2 diagrams such as Logicator (Newsom, 1996) and Flowol (Bowker, 1998). However, environments based on Type 1 diagrams, such as Control Insight (Rogers & Steeg, 2000), also exist;

- Some, but by no means all, texts define what the elements of a Type 1 diagram represent (Pilliner & Snashall, 1987; Branson, 1991; Simpson, 1991; UNILAB 1992; Haslam, 1993; Cave, 1994, 1995; Steeg et al, 1994; Barlex, 1997; Norman et al, 1995; Sage et al, 1995; Sage & Thompson, 1996; RCA, 1997a, 1997b), but in most cases there is very little emphasis put on this definition. Fewer define the elements of Type 2 diagrams or
distinguish the two types of diagram clearly (Steeg et al, 1994; Sage et al, 1995; RCA 1999). This pattern reflects examination syllabuses where the definition of diagram elements is generally absent;

- The actual use of Type 1 diagrams in texts is often inconsistent. For example, signals may often be represented by both blocks and lines in different diagrams, signals and functions may be confused and input and output signals are widely omitted;

- The focus is generally on distinguishing between open and closed loop control and defining feedback, presumably reflecting the emphasis on this aspect in the National Curriculum. This distinction is not always made accurately; where Type 1 diagrams are well defined feedback generally is as well (Pilliner & Snashall, 1987; Haslam, 1993; Cave, 1994, 1995; Barlex, 1995, 1997; Steeg et al, 1994; Norman et al, 1995; Sage et al, 1995; Sage & Thompson, 1996; RCA, 1997a, 1997b).

- The main emphasis is on contexts where ‘hard’ systems thinking, supported by Type 1 diagrams, is appropriate (control technologies). However, even here only a few texts provide any guidance on how to actually use systems ideas to support designing or analysis (Branson, 1991; UNILAB 1992; Steeg et al, 1994; Barlex, 1997; Sage et al, 1995; RCA, 1997a, 1997b);

- Where social contexts are introduced there is generally an implicit assumption that the same ‘hard’ systems thinking tools are appropriate. In some instances other diagram types are introduced but the fact, or the ways, that they are different is not always fully discussed (RCA 1996, 1997a, 1999; Sage & Thompson, 1996).

Given the above, it is not surprising that personal experience indicates that the understanding and application of systems ideas in both secondary teachers and their pupils is generally not well developed. For example: Drawn systems diagrams are often hybrids of Type 1 and 2 diagrams; pupils will generally only use systems ideas if required to; the notion that these
ideas might be a tool to make D&T easier does not seem to be widespread. The extent of these problems will be the subject of further work built on this paper.

Conclusions; implications for practice and further work

The study summarised here is intended to form part of the background to a detailed investigation of both the understandings that pupils and teachers hold of control and systems ideas and of ways in which they might be assisted in developing and using such ideas to support high quality work in D&T.

In the meantime, the latest version of the UK National Curriculum for D&T has an increased weight given to the heading 'Systems & Control'. At the same time, the evidence from OfSTED inspections is that this is a weak area of the D&T curriculum. The following are offered as initial steps that could be taken to provide better support for teachers and their pupils in this area:

- Exam syllabuses should define the meanings of Type 1 diagram elements in the same way that they generally do for Type 2 diagrams and always do for other diagrams such electronic or pneumatic symbols.
- Secondary teachers (and texts) should define the meanings of all diagram elements that they use, ensure that these elements are then used consistently and make explicit the purposes and limitations of the various system diagrams used.
- Pupils also need examples of the way systems thinking can be used to make the process of analysis more accessible. This is important for those designing their own systems and for those analysing existing systems. Again these are identified by OfSTED as weak areas of the curriculum and yet are areas where the potential offered by systems thinking is particularly strong.
• At more advanced levels of the curriculum it might be sensible to investigate whether other diagram systems, in addition to Types 1 and 2, might be helpful to pupils and, if so, which ones.

(3500 words)

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